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ADVANCED CONCEPTS IN STRUCTURAL MATERIALS AND TESTING. PART I. THE APPLICATION OF RANDOM SIGNAL CORRELATION TECHNIQUES TO ULTRASONIC FLAW DETECTION IN SOLIDS

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13. ABSTRACT

The work performed under this program can be subdivided into two areas. The first deals with the application of random signal correlation techniques to ultrasonic flaw detection in solids and the second deals with the development of modulated microstructure heat treatable steel.

The portion of this work dealing with the application of random signal correlation techniques to ultrasonic flaw detection in solids consists of applying random signal radar techniques to ultrasonic flaw detection and determining the consequent improvements in range and resolution over existing systems. The accomplishments to date are:

1. A random signal ultrasonic flaw detection system, has been constructed and operated.
2. It has been demonstrated that the resolution of the system is independent of the length of the transmitted signal. This indicates that a much lower peak to average power ratio can be used than is possible with pulse-echo systems.
3. It has been experimentally demonstrated that signals which are 1,000 times too small to be detected by a current pulse-echo system can be used by our system.
4. The smallest flaw that can be viewed by our present system agrees with theoretical calculations and is the order of .001 inches.
5. A clutter avoidance scheme has been invented which should permit the system to maintain its demonstrated advantages in an environment containing many detectable flaws.

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PART I

The Application of Random Signal Correlation Techniques to Ultrasonic Flaw Detection in Solids

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iii

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REPORT SUMMARY

1. Technical Problems

Conventional ultrasonic flaw detectors are presently used to test all manner of manufactured metal objects ranging from ingots to welded steel vessels. They are also important for the detection of flaws in metal objects that may develop cracks during their lifetime such as airplane structural members and submarine hulls. The oldest and most widely used ultrasonic flaw detection technique is that of pulsed echo which depends on the reflection of a burst of sound from the flaw to be detected.

In pulse echo systems, piezoelectric transducers are used to transmit a burst of several wavelengths of megacycle sound into the test object. The beam of sound emerging from the transducer will be reflected back towards it if it encounters a suitably angled inhomogeneity. Any sound reflected back towards the transducer is reconverted into an electrical signal whose time of occurrence and amplitude give information respectively about the distance of the flaw from the transducer and about its size. The difficulties of pulse echo flaw detectors arise from the fact that to avoid range ambiguity it is necessary to wait until the most distant echo has returned before transmitting another pulse. Furthermore, to obtain fine range resolution, that is to be able to distinguish between two closely adjacent flaws, it is necessary to transmit a correspondingly narrow pulse. We therefore end up with the situation described by the equation:

$$\frac{\text{Maximum Range}}{\text{Range Cell}} = \frac{\text{Burst Interval}}{\text{Burst Width}} = \frac{\text{Peak Power}}{\text{Average Power}}$$

namely that the ratio of peak transmitted power to average transmitted power has to be at least as large as the ratio of the maximum range to the desired resolution, a ratio which can easily be on the order of 1000 or more. Since transducers are limited in the peak power that they can handle by electrical breakdown effects, this phenomenon strongly limits the resolution that can be obtained, particularly when viewing relatively large ranges.

The other major problem faced by pulse echo flaw detectors is the fact that strongly absorbing material makes it necessary to use the largest possible average transmitted power if the returning echoes are to be larger than the thermal noise of the receiver. Since ultrasound transducers are strongly limited in power handling capacity by overheating, this limits the range of pulse echo systems when used in strongly sound absorbing or scattering materials.

In fact, according to one of the standard references on this subject, the range over which flaws can be sensed is at present limited to 10 centimeters or less in strongly sound absorbing or scattering materials such as high alloy steels and ceramics.

2. General Methodology

Some years ago, Professor Cooper, of Purdue University, one of our consultants in this work, and his associates developed the so called Random Signal Radar system[1]. By using a transmitted signal, which varies randomly with time, this system overcomes the peak to average power

1. C. D. McGillem, G. R. Cooper and W. B. Waltman, "Use of Wideband Stochastic Signals for Measuring Range and Velocity," EASCON '69 Convention Record, pp. 305-311, 1969.

problem, since it is possible with it to transmit almost continuously without losing range resolution. Furthermore by integrating the output signal over long time periods it is possible to detect echoes which on arrival at the receiver are less than the spontaneous thermal noise produced by the receiver amplifier.

This project consists of applying random signal radar techniques to ultrasonic flaw detection, and determining the consequent improvements in range and resolution over existing systems.

3. Technical Results

The accomplishments achieved to date in this program may be summarized as follows:

1. A random signal ultrasound flaw detection system, the first of its kind, has been constructed and operated.

2. It has been demonstrated that the resolution of random signal system is independent of the duration of the transmitted signal which indicates that much lower peak to average power ratio can be used than is possible with conventional systems. The above conclusion indicates that the random signal correlation system should therefore be capable of much greater range and/or resolution than is possible with current pulse echo systems.

3. It has been experimentally demonstrated that the use of correlation and time integration techniques enables the system to achieve a signal to noise ratio correlation gain of the order of 10^4. Thus signals which are thousands of times too small to be detected by current pulse echo systems can be used by our system. For a given transmitted power the system should thus have a range greatly exceeding that of existing pulse echo flaw detectors.

4. The smallest flaw that can be detected by our system at the present is of the order of 25 microns which is far smaller than its present lower resolution limit of 250 microns. It should be possible to improve the range resolution by an order of magnitude by going to correspondingly higher frequencies.

5. Unwanted echoes reaching the receiver from flaws outside the range cell are known as clutter. These so called clutter echoes can be minimized by shortening the transmitted signal until its length is no longer than the time of flight through the range cell, and lowering the transmitted burst repetition frequency to the value used in conventional pulse echo systems. However, this procedure completely negates the advantage of noise in lowering the peak to average transmitted power ratio. A clutter avoidance scheme has been invented which should permit this system to maintain its demonstrated advantages even in an environment containing many detectable flaws.

4. Implications for Further Research

Having proved the feasibility of a random signal ultrasound flaw detection system which can detect 25 micron flaws, we will proceed to the design and construction of a system that can detect flaws which are 10 times smaller, in ceramic or other parts with flat surfaces. We will then develop techniques which allow the system to scan test pieces with irregular surfaces.

5. Special Comments

We have experimentally demonstrated a random signal ultrasound flaw detection system which is orders of magnitude more sensitive than current pulse echo systems. This can be used either to view much thicker samples than can be handled by current systems, or to detect much smaller flaws than can presently be detected.

Work in our laboratory has shown that the use of random signal techniques promises improvements in liquid flow measurement systems which are at least as great as those expected for flaw detection systems.

INTRODUCTION

Conventional ultrasonic pulse echo systems are widely used to detect flaws produced during the manufacture or use of many types of metal and ceramic components. These systems transmit short bursts of radio frequency ultrasound into the test object and display the echoes reflected from inhomogeneities oscillographically. The time of occurrence and amplitude of these echoes can be related respectively to the location and magnitude of the sound reflectors.

To avoid range ambiguities in systems that transmit the same waveform in each burst, it is necessary to wait until the echo from the most distant target has returned before another burst can be transmitted. Therefore, the repetition period T of the r.f. bursts is limited by

$$T \leq \frac{2R_{max}}{c} \qquad (1)$$

where c is the velocity of sound and R_{max} the maximum range from which echoes can be detected.

To obtain fine range resolution, it is necessary to transmit a correspondingly narrow burst of r.f. of length $\Delta\tau$ where

$$\Delta R = \frac{c\Delta\tau}{2} \qquad (2)$$

From equations (1) and (2) the ratio of peak to average transmitted power can be written as

$$\frac{P_{peak}}{P_{avg}} = \frac{T}{\Delta\tau} \leq \frac{R_{max}}{\Delta R} \; . \qquad (3)$$

Thus for pulse echo systems the ratio of peak to average transmitted power has to be at least as large as the ratio of the maximum range to the desired range resolution. This ratio will usually be on the order of 10^2 or more in practical systems. Since transducers are limited in the peak power that they can handle by electrical breakdown effects, the large peak to average power ratio required can limit the maximum ratio of range to resolution that can be obtained by pulse echo systems.

The other major problem faced by pulse echo flaw detectors is the fact that strongly sound absorbing material makes it necessary to use the largest possible average transmitted power if the returning echoes are to be larger than the thermal receiver noise.[1] Since ultrasound transducers are strongly limited in average power handling capacity by overheating, this limits the range of pulse echo systems when used in strongly sound absorbing or scattering materials.

Since the thermal noise power of amplifiers is proportional to their bandwidth, it can be shown that the ratio of the signal to noise power at the output of a flaw detection system to that at the output of the echo receiving amplifier is given by the expression

$$\frac{SNR|_{out}}{SNR|_{in}} = \frac{B_{in}}{B_{out}} \tag{4}$$

where B_{in} and B_{out} are respectively the bandwidths at the input and output of the system.

In the pulse echo systems currently in use, the bandwidth of the signal received at the receiver and the bandwidth of the output signal emerging from the detector are approximately the same. Thus these systems are not able to improve the signal to noise ratio of the received echo, and the received echo must therefore be much larger than the thermal noise of the echo amplifier.

In current and as yet largely unpublished work, Woodmansee[2] et al and Seydell[3] use so called time averaging techniques to improve the input signal to noise ratio of flaw detection systems by integrating the echo signals over relatively long time periods, thus effectively restricting the output bandwidth.

Woodmansee achieves time integration by means of a lock-in amplifier whereas Seydell digitizes the echo signal and uses a digital computer. Both systems use conventional short bursts of r.f. as their transmitted signal and therefore require high peak to average power ratios.

The random signal flaw detection system described in the remainder of this paper falls into the class of correlation receivers, and, like the systems of Woodmansee et al and Seydell, can produce a huge enhancement in the input signal to noise ratio, by the use of time integration. In addition, it uses noise as the transmitted signal, so that the resolution along the ultrasound beam is shown to be independent of signal duration. Consequently the peak to average transmitted power can be kept close to unity, so that the maximum power that can be transmitted is no longer limited by transducer electrical breakdown. The transmission of long duration signals is shown to lead to a deterioration of system performance in the presence of distributed targets, due to incoherent 'clutter' type echoes from flaws outside the range cell from which the system is receiving coherent echoes. A technique involving the

the use of two focused transducers with overlapping radiation patterns is shown to overcome this problem.

The use of a random signal or 'noise' in imaging systems has been considered by a number of authors [4-8] in connection with radar but appears to have been first demonstrated experimentally, again in radar, by McGillem, Cooper and Waltman[9]. Additional random signal radar systems have been described by Poirier[10], Craig et al[11], Carpentier[12] and Smit and Kneefel[13]. Random signal systems do not seem to have been used for ultrasonic flaw detection previously, although a pseudo-random code ultrasonic doppler system has been used for blood flow measurement[14] and a random signal ultrasonic doppler system is being developed for the same purpose.[15-17]

SYSTEM DESCRIPTION AND THEORY

System Operation

The block diagram of the basic random signal system is shown in Fig. 1. The noise or r.f. source produces electrical signals which are converted into ultrasound and transmitted into the sample by the piezoelectric transducer. Echoes reflected from inhomogeneities are picked up by an identical receiving transducer and are re-converted into electrical signals. The received signal is then correlated with a sample of the transmitted signal which has been delayed by τ_d, by means of a delay line.

The amplified echo signal together with the reference signal emerging from the delay line enter the correlator which consists of a multiplier followed by an integrator in the form of a low pass filter. In the presence of the target shown, the system will produce a non-zero output when the delay τ_d imposed on the reference signal by the delay line equals the time of flight τ_s of the acoustic signal from the transmitting transducer to the target and back to the receiver. Under these circumstances the noise signals entering the two inputs of the correlator are identical, causing it to produce a non-zero output. It is shown below that if $|\tau_s - \tau_d| \gg 1/\pi B$ where B is the bandwidth of the transmitted signal, the signals entering the correlator are uncorrelated, so that its time averaged output is zero. If the length of the delay line is changed slowly with time, τ_d varies, so that the system scans over a line in the test object, producing an output on each occasion that the time varying delay τ_d is nearly equal to the time of flight τ_s to an ultrasound reflecting flaw.

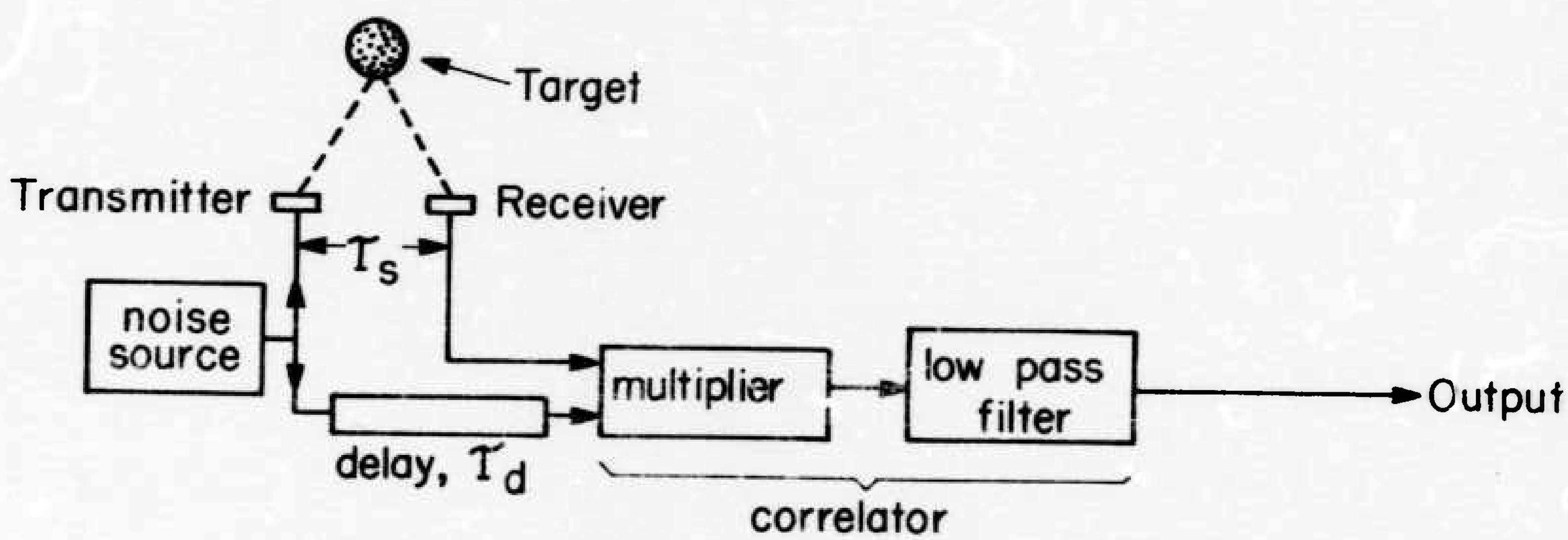

FIG. 1 BASIC RANDOM SIGNAL SYSTEM.

A practical version of the random signal flaw detection system is shown in Fig. 2. The transmitting and receiving transducers are arranged so that their 'antenna patterns' overlap in the cross hatched region. The variable delay line is made up of two identical ultrasound transducers in a water bath whose separation can be varied by a micrometer.

The amplified echo signal and the reference signal emerging from the delay line are passed through Schmitt triggers acting as clipping circuits.[A] It is shown later that this way of transforming a noisy multi-valued signal into a signal which can only have one of two magnitudes, merely reduces the effective signal to noise ratio by a factor $\frac{2}{\pi}$ if the signal to noise ratio is much less than unity. The squared echo and reference signal are fed into a correlator whose gated output is displayed on one axis of a pen recorder. The other axis of the recorder is connected to a micrometer which controls the distance between the transducers of the delay line. The advantage of clipping the echo and reference signals is that the correlation function can be performed by a simple 'exclusive-or' gate followed by a 'nor' gate, the output of which is then fed into a low pass filter for integration as shown in Fig. 2. The purpose of the 'nor' gate is to insure that only correlator outputs from the desired echoes reach the integrator and that thermal noise generated at other times, as well as signals leaking directly from the transmitter to the receiving transducer are excluded. This is achieved by allowing the 'nor' gate to pass signals only during the time that reference signals are emerging from the delay line. To scan a portion of a specimen, the separation between the transducers of the delay line is varied by means of a micrometer which also causes the pen of the recorder to traverse. Whenever the reference delay τ_d is approximately equal to the time of

[A]See footnotes page 31.

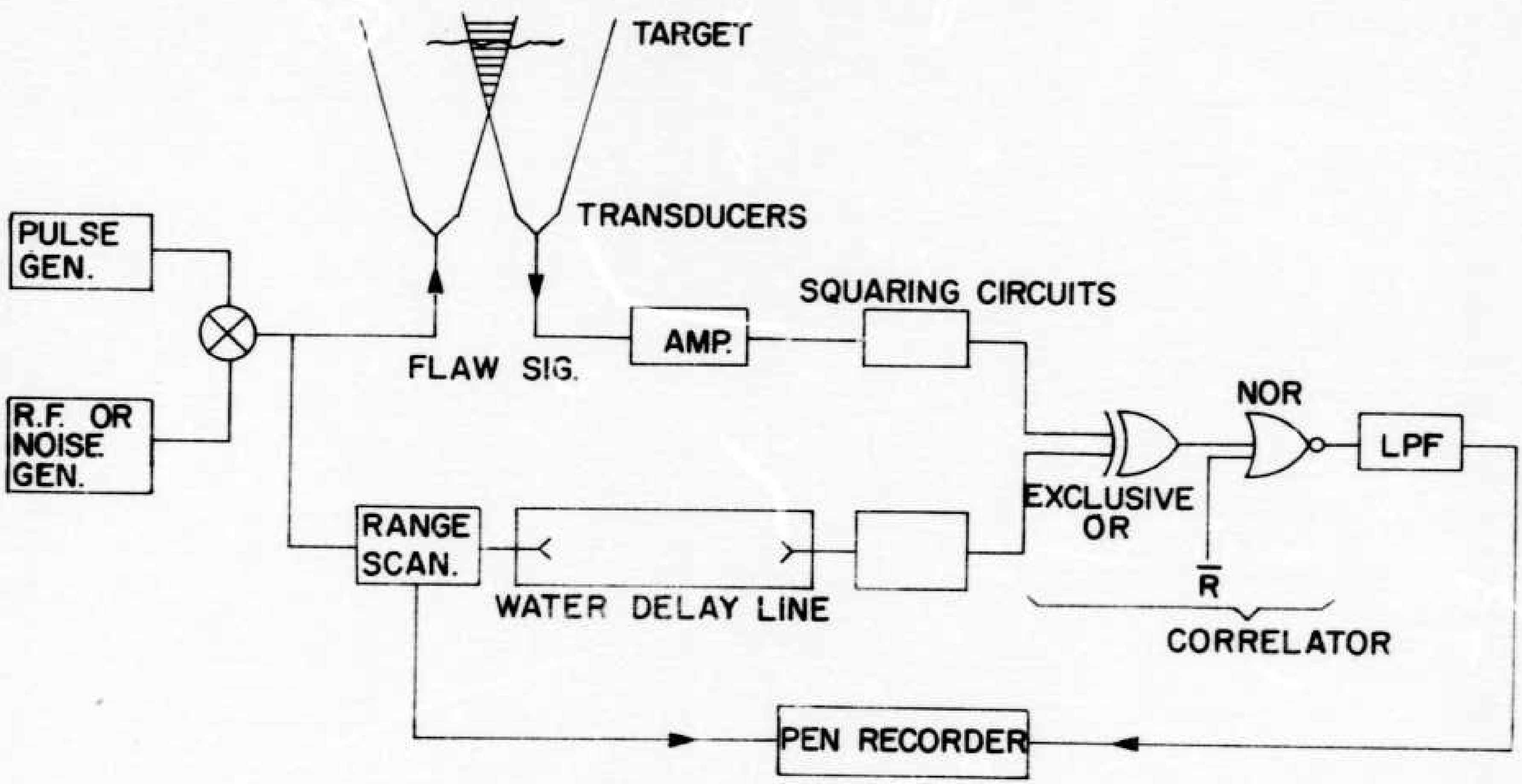

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FIG. 2 EXPERIMENTAL RANDOM SIGNAL FLAW DETECTION SYSTEM EMPLOYING SIGNAL CLIPPING AND POLARITY COINCIDENCE CORRELATOR.

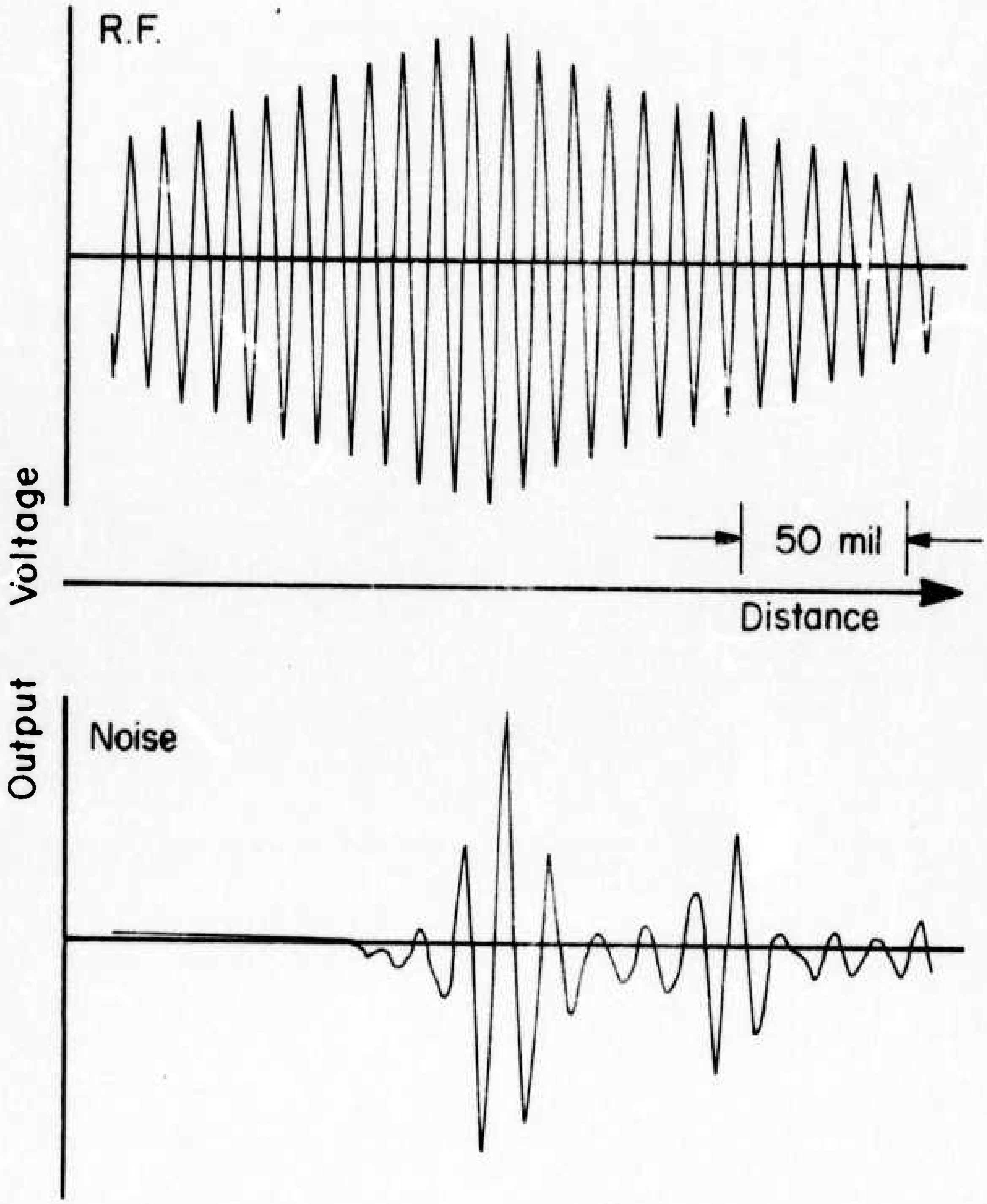


FIG. 3 COMPARISON OF SYSTEM OPERATION USING PERIODIC 4 µSEC BURSTS OF RF AND NOISE AS TRANSMITTED SIGNAL.

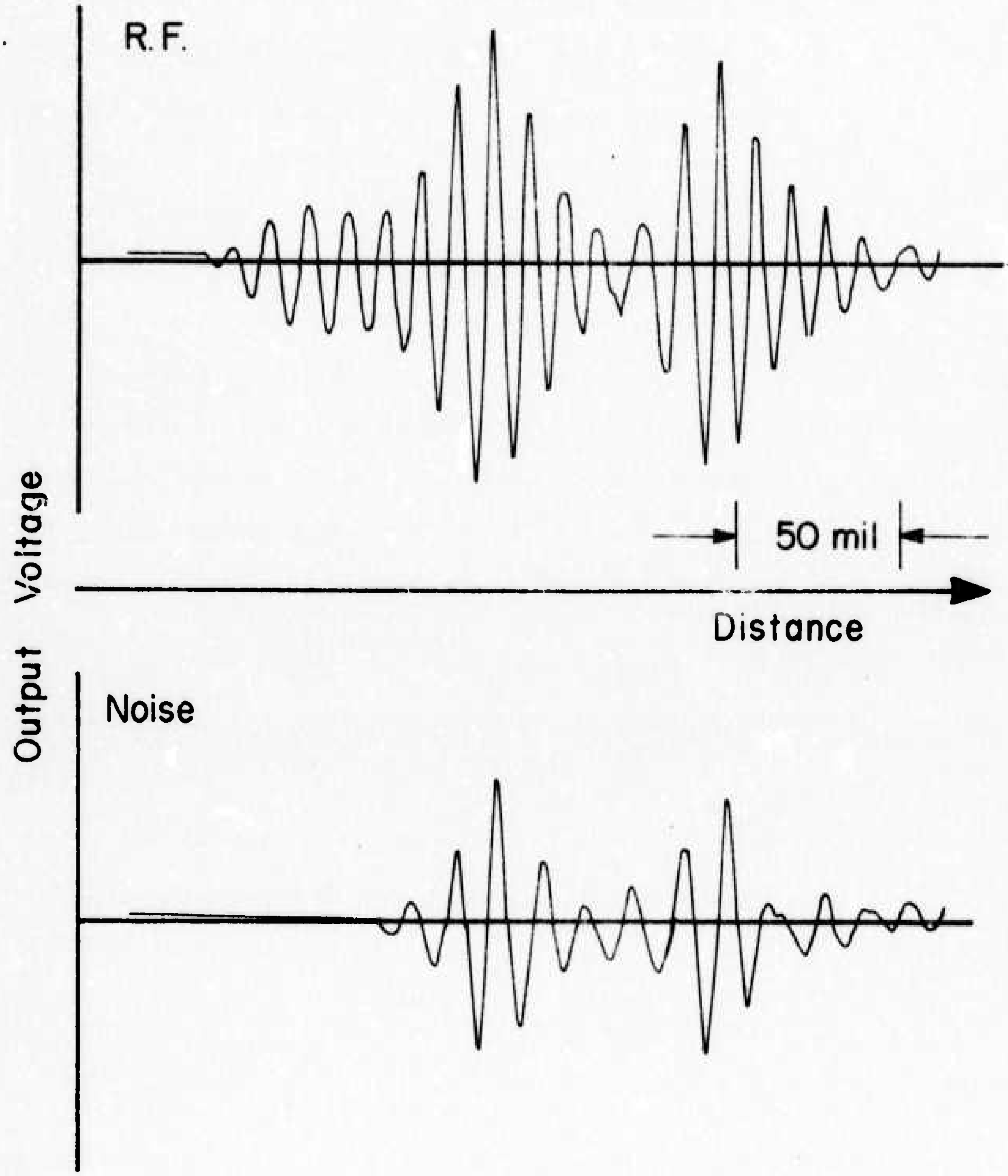


FIG. 4 COMPARISON OF SYSTEM OPERATION USING 1 μSEC BURSTS AS THE TRANSMITTED SIGNAL.

flight τ_s, the correlator produces an output which is displayed by the pen recorder. A typical output showing the two surfaces of a 1 mm diameter wire in water is shown in Figs. 3 and 4.

Analysis of System Operation

Under conditions where the thermal amplifier noise is negligible compared to the echo signal, where no signal clipping is used, and where the correlator is of the analog type, the system can be modeled, as shown in Fig. 5 where both the reference signal delay τ_d and the signal time of flight delay τ_s, are represented by delay lines. The correlator output corresponds to the time average of the product of the two delayed versions of the transmitted noise signal. This time average is the autocorrelation function $R_x(\tau_s - \tau_d)$ of the noise signal $x(t)$.

Figure 6 shows the time average of the correlator output for a bell shaped transmitted noise spectrum

$$S_x(f) = \frac{B^2}{B^2 + (f - f_o)^2} \tag{5}$$

where f_o is the center frequency and 2B the bandwidth. The correlator output $R_x(\tau_s - \tau_d)$, is the inverse Fourier transform of $S_x(f)$ and may be written as

$$R_x(\tau_s - \tau_d) = e^{-\pi B|\tau_d - \tau_s|} \cos 2\pi f_o(\tau_d - \tau_s) \tag{6}$$

It can be seen that the time average of the correlator output reaches a maximum when $\tau_s = \tau_d$. It is also clear that the correlator output falls to 1/e of its maximum when $|\tau_d - \tau_s|$ equals $1/\pi B$. From equation 2 it follows that the range resolution of this system is

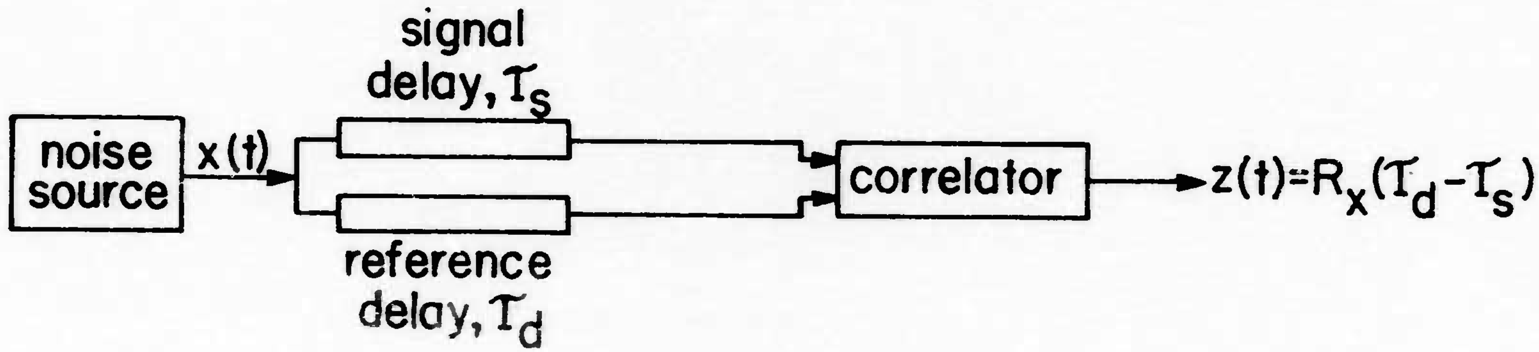
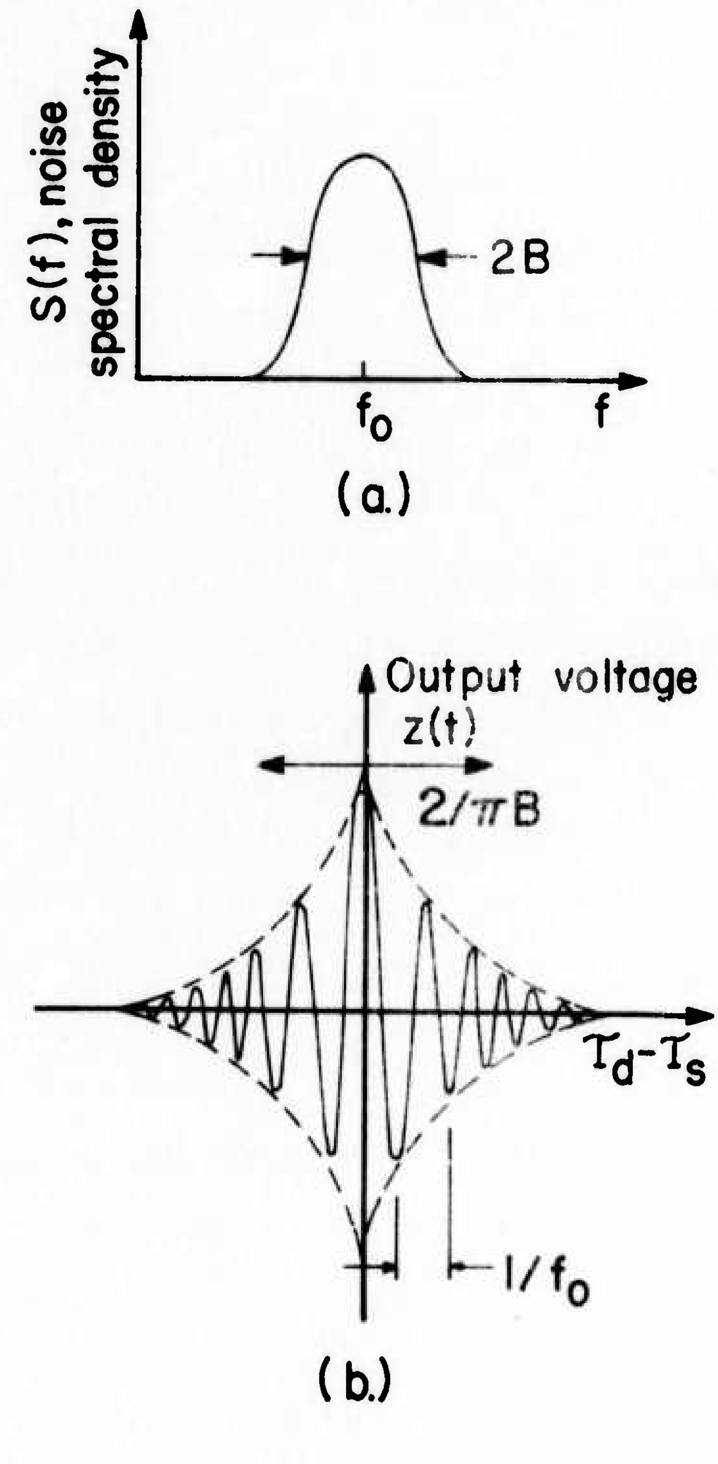


FIG. 5 MODEL OF BASIC RANDOM SIGNAL SYSTEM.

FIG. 6 SYSTEM WAVEFORMS

(a) SPECTRUM OF TRANSMITTED NOISE SIGNAL

(b) CORRELATOR OUTPUT VOLTAGE AS RANGE CELL IS SCANNED THROUGH TARGET.



$$\Delta R \sim \frac{c}{2\pi B} \tag{7}$$

If the bandwidth of the transmitted signal approaches the maximum signal frequency, then it can be shown that the range resolution approaches the theoretical minimum of one-quarter wavelength of the maximum transmitted frequency.

Equation 7 is an extremely important result since it demonstrates that the resolving power of the random signal system depends purely on the bandwidth and not on the time duration of the transmitted signal as in pulse echo systems. Furthermore since every burst of transmitted noise is different, no range ambiguity results even if bursts are transmitted before the last echo of the previous burst has returned to the receiver. A random signal system can thus transmit noise almost continuously so that the ratio of peak to average transmitted power can approach unity.

It is of interest to point out that the range resolution of the random signal system as given by equation 7 is the same as that of a pulse echo system transmitting a periodic signal having the same spectrum as that of the noise signal. For instance if such a pulse echo system transmits bursts of r.f. having the form of equation 6, it can be seen that two targets will be resolved if their range differs by

$$\Delta R \sim \frac{c\Delta\tau}{2} \tag{8}$$

where $\Delta\tau$ is the time required for the r.f. burst to decline from its peak value to e^{-1} of its maximum height. From Fig. 6 clearly

$$\Delta\tau = \frac{1}{\pi B} \tag{9}$$

combining equations 8 and 9 gives the range resolution of the pulse echo system as

$$\Delta R \sim \frac{c}{2\pi B}$$

which is seen to be identical to the resolution of the random signal system, given by equation 7.

<u>Signal to Noise Ratio Improvement.</u>

A very important property of the random signal flaw detection system is that its sensitivity can be made almost arbitrarily large by simply increasing the integration time of the correlator.

As shown in equation 4, the ratio of the output signal to noise ratio to that at the input is equal to the ratio of input to output bandwidths. For pulse echo systems this ratio was shown to be unity since input and output bandwidths are comparable. This however, is not the case for the random signal system since the bandwidth at the receiver is determined by the transmitted bandwidth B_{in} while the output bandwidth B_{out} equals the reciprocal of the integration time T of the correlator which can be made arbitrarily long. Thus the signal to noise ratio improvement provided by the random signal system is given by the equation

$$\frac{SNR|_{out}}{SNR|_{in}} \sim \frac{B_{in}}{B_{out}} \equiv BT$$

A more exact calculation for the clipped signal system actually used here, is given in the appendix and predicts a correlation gain for small input signal to noise ratios of

$$\frac{SNR|_{out}}{SNR|_{in}} \sim \frac{2\alpha}{\pi} BT \qquad (10)$$

where α is the mark space ratio and B the bandwidth of a Gaussian noise transmitted signal and T is the integration time of the correlator. Since this result was derived for a stationary random transmitted signal, it must also be true for periodic transmitted signals e.g. short bursts of r.f. as used in conventional pulse echo systems.

Experimental results described below verify equation 10 and demonstrate that enhancement ratios of thousands can be obtained.

<u>The Clutter Problem and its Solution</u>

As explained earlier, if the ratio of peak to average transmitted power is to be made small, the mark space ratio (α) should be as close as possible to its maximum value of unity. If the transmitted signal simultaneously covers targets inside and outside the range cell,[B] signals from both regions are received simultaneously. The echoes from targets outside the range cell are uncorrelated with those from inside the range cell, and therefore do not affect the mean value of the output signal corresponding to the target under observation. They do however increase the effective system input and output noise. These so called 'clutter' echoes can be minimized by shortening the transmitted signal until its length is no longer than the time of flight through the range cell, and lowering the transmitted burst repetition frequency to the value used in conventional pulse echo systems. However, this procedure completely negates the advantage of noise in lowering the peak to average transmitted power ratio.

There exists a technique[15] illustrated in Fig. 7, which avoids clutter even in the presence of continuous transmitted noise. Here focused transducers are positioned such that the beam pattern intersects the receiver beam pattern only in that region in which the range cell is located. Any echoes from targets outside this small region approach the receiving transducer at angles at which it is extremely insensitive. Therefore the only echoes that can be recognized by the receiver are those from targets within the region where the transmitter and receiver beam patterns overlap. Clutter type signals can be avoided completely by making the overlap region comparable to the size of the target.

This technique for clutter avoidance circumvents the only apparent disadvantage of the large mark-space ratio which can be used in random signal flaw detection systems. This should be particularly useful when examining materials with many grain boundaries, where clutter problems would normally be severe.

The Correlator Output Waveform

The correlator output as displayed on the pen recorder for a given distribution of sound reflecting inhomogeneities may be calculated as follows. Let the acoustic reflection coefficient be $a(\tau)$, for targets situated so that the time of flight to and from the transducers is τ. The range R of a target for which the time of flight is τ is

$$R = \frac{c\tau}{2}$$

if the transducers are assumed adjacent.

Ignoring absorption effects, the echo received from a transmitted signal $x(t)$ which reach the correlator will be

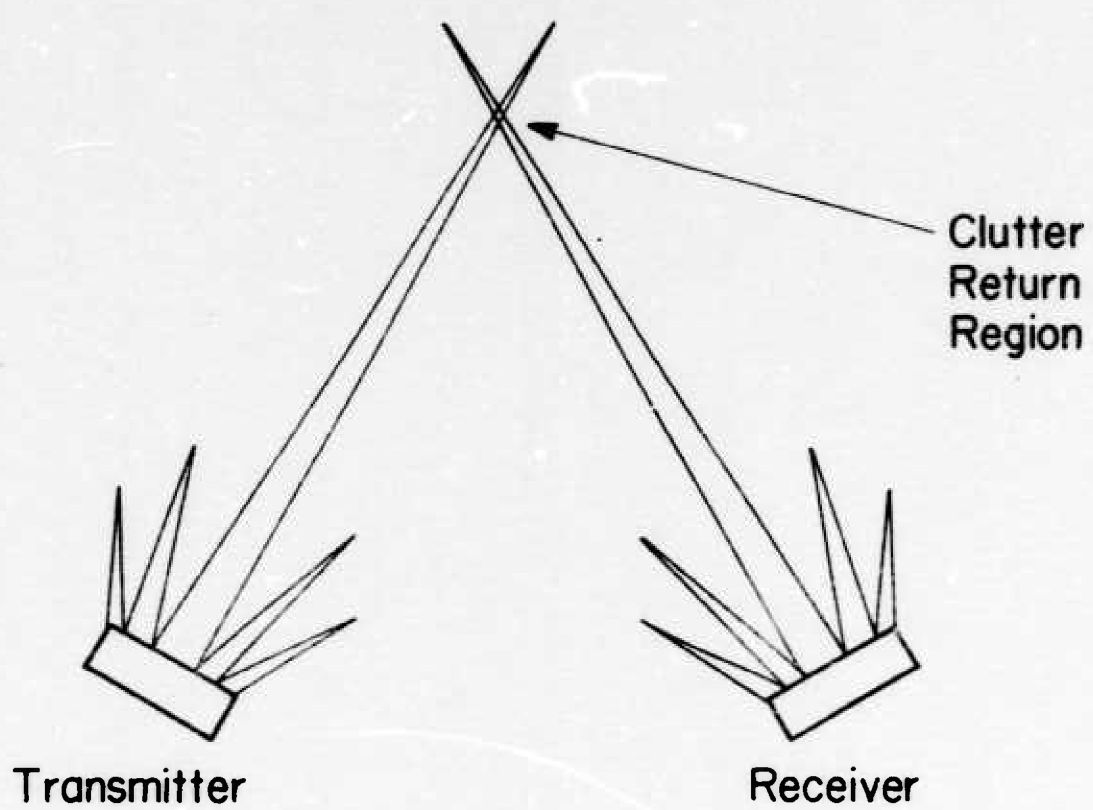


FIG. 7 CLUTTER AVOIDANCE SYSTEM.

$$y(t) = \int_{-\infty}^{\infty} a(\tau)\, x(t - \tau)\, d\tau$$

Since the reference channel input to the correlator is $x(t - \tau_r)$ where τ_r corresponds to the delay line setting, the time averaged output of an analog correlator will be

$$z(\tau_r) = E\left\{x(t - \tau_r)\int_{-\infty}^{\infty} a(\tau)\, x(t - \tau)\, d\tau\right\}$$

where $E\{\ \}$ stands for expectation value. Since neither t nor τ_r are variables of integration, the expectation can be brought inside the integral giving the time average of the correlator output as

$$z(\tau_r) = \int_{-\infty}^{\infty} a(\tau)\, R_x(\tau - \tau_r)\, d\tau \qquad (11)$$

An acoustic reflector whose dimensions are large compared to the transmitted wavelengths may be treated as a reflecting surface for which $a(\tau)$ becomes a delta function. Therefore for a single reflecting surface with time of flight τ_a, equation 11 becomes

$$z(\tau_r) = \int_{-\infty}^{\infty} \delta(\tau-\tau_a)\, R_x\, (\tau-\tau_r)\, d\tau = R_x(\tau_a-\tau_r) \qquad (12)$$

We see therefore that each reflecting surface will produce the auto-correlation function of the transmitted spectrum at the pen recorder output, with the central peak of the spectrum corresponding to the location of the reflecting surface. This result applies to both random and periodic transmitted waveforms. Examination of the form of the system outputs in Figs. 3 and 4 shows that the experimental outputs correspond to the auto-correlation function of a long burst of r.f. in one case, and of Gaussian noise with a bell shaped spectrum in the other.

To produce a system output which most closely resembles the inhomogeneity profiles, the correlator output could be subjected to some form of deconvolution process, either using a digital computer, as has been done by Seydell[3], or by some form of electrical network. However this procedure tends to enhance any noise mixed in with the original echo, and is therefore only useful in the rather rare cases where the input signal to noise ratio is high.

EXPERIMENTAL RESULTS

Range Resolution

The system described above has been operated successfully to detect artificial flaws consisting of wires in water, both when transmitting ultrasound in bursts of 4.8 MHz sine waves (subsequently referred to as "r.f.") or bursts of 2 MHz bandwidth random signals with a 4.8 MHz center frequency (subsequently referred to as "noise"). In the experiments described here, the transmitting and receiving transducers of the system were arranged almost parallel so that their beams overlapped as shown in the shaded region in Fig. 2. By moving one of the transducers in the water delay line with a micrometer, the internal delay of the so called reference signal was changed, so that the system could scan across a series of targets.[C] In the experiments described here, both the wire targets and the transducers were immersed in a water bath. The outputs of the system were recorded by a pen recorder which produces the type of display shown in Fig. 3. Here the X axis corresponds to the spatial coordinate and the Y axis to the strength of the echo from various targets.

Figure 3 corresponds to the observation of a 1 mm copper wire; the upper half of the figure shows the output when a 4 μ sec. burst of 4.8 MHz r.f. is transmitted and the lower half shows the output for 2 MHz bandwidth noise of the same burst length. Notice that the r.f. signal can detect the presence of the wire but cannot resolve the front and back edges. The noise signal which has the same duration as the r.f. signal but larger bandwidth, is easily able to resolve these edges. However when a 1 μsec pulse is used, as shown in Fig. 4, the r.f. is also able to resolve the edges but at a cost of higher peak to average power. Inspection of Fig. 3 shows that this particular system, using noise, could have resolved targets with a separation as low as 250 microns. Figure 8 shows the correlator output for a 1 mil wire. It is clear from this plot that because of its great sensitivity the system is able to detect targets far smaller than its resolution limit.

It should be noted that the output pattern produced by the system when using noise agrees very closely with that predicted theoretically and illustrated in Fig. 6. As predicted, it is clear from Figs. 3 and 4 that for noise the resolution does not depend on signal duration but only on bandwidth. It is also clear from these figures that the range resolution of noise is much higher than that of pulsed r.f. of equal duration but lower bandwidth. It should be noted however that the improvement of the signal to noise ratio produced by our correlation type system is evident not only when transmitting noise but also when transmitting pulsed r.f..

<u>Signal to Noise Enhancement Measurements</u>

The correlation gain of a system using clipped signals and a polarity coincidence correlator is derived in the appendix, and for input signal to noise ratios much less than unity was given in equation 10 as

$$\frac{SNR|_{out}}{SNR|_{in}} \sim \frac{2\alpha}{\pi} BT$$

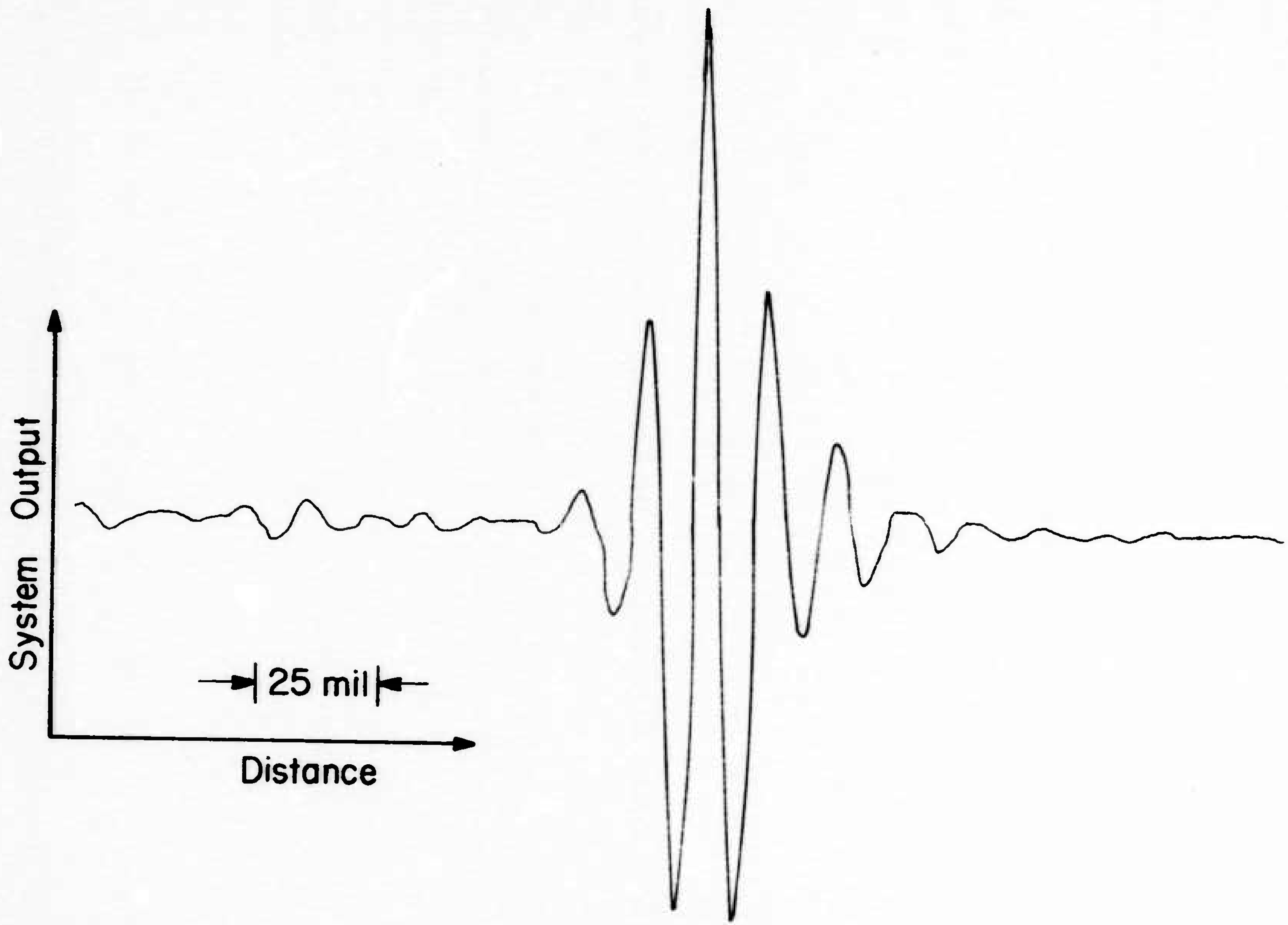


FIG. 8 DETECTION OF ONE MIL Au WIRE IN WATER AT 15 CM RANGE.

20a

For our low-pass filter pen recorder combination with a measured time constant of T = 120 μsec and transmitted bandwidth of 2MHz, equation 10 predicts a signal to noise ratio enhancement of approximately 8×10^3 with the mark-space ratio of 1/20 that was used. The measured signal to noise ratio enhancement agreed with the predicted value to well within the experimental uncertainty.

It is believed that the signal to noise enhancement ratio quoted above could be increased by an order of magnitude simply by increasing the mark-space ratio to 1/2 from 1/20. This was not experimentally verified since it was already difficult to measure the enhancement ratio of 8×10^3. Further increase in enhancement would have been extremely difficult to measure and probably inaccurate due to leakage effects at high attenuations.

Figure 9 shows the correlator output for a 3 mil Au wire target with superimposed outputs corresponding to the transmitted signal attenuation of 20 db over the previous larger output. It is clear that even after 40 db attenuation of the input signal, the output signal to noise ratio is still greater than unity. It should also be noted that the received signal at the output of the amplifier was completely buried in thermal receiver noise after only 20 db attenuation was imposed on the transmitted signal. These results clearly indicate that the random signal system can recover signals that are deeply buried in noise.

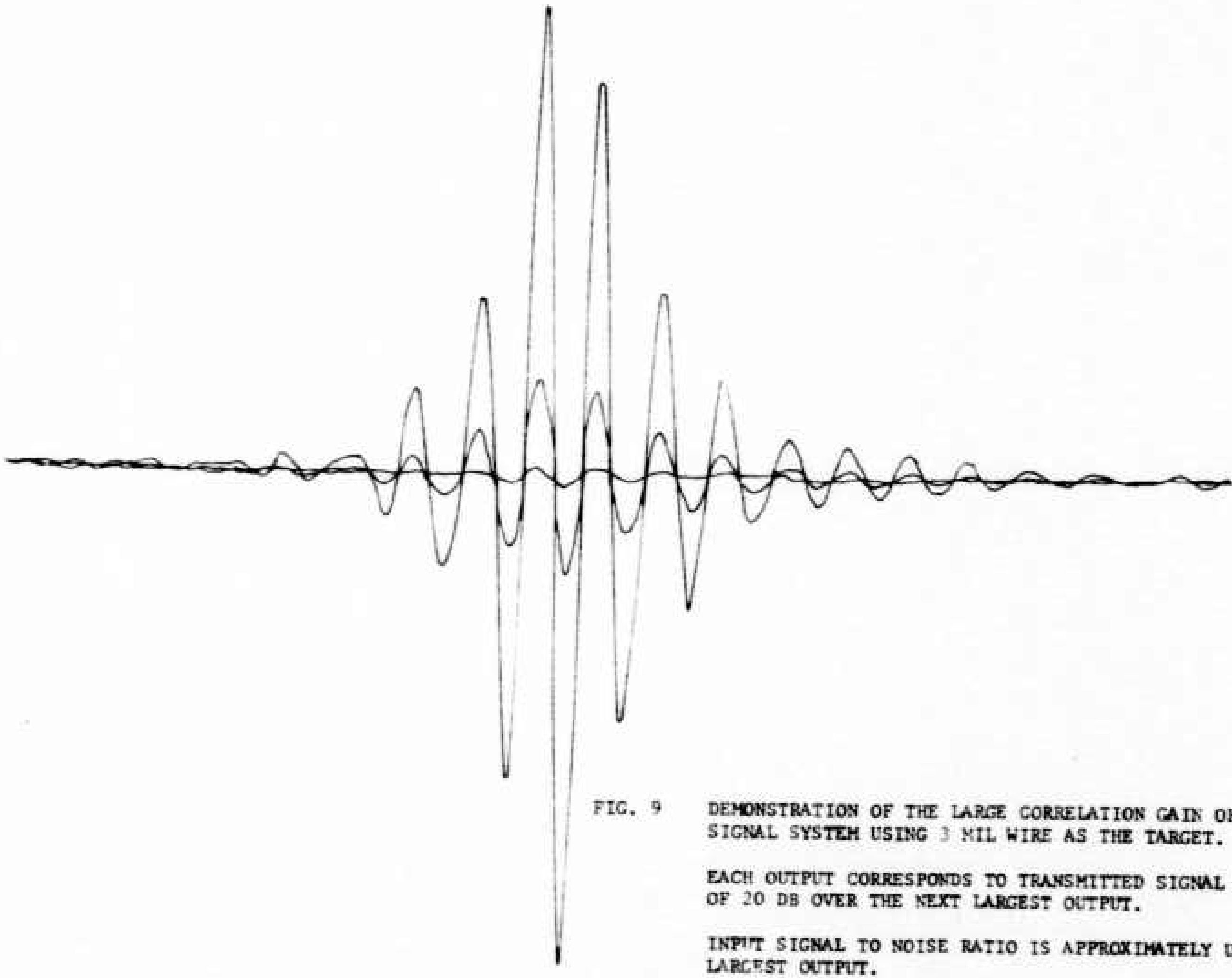


FIG. 9 DEMONSTRATION OF THE LARGE CORRELATION GAIN OF THE RANDOM SIGNAL SYSTEM USING 3 MIL WIRE AS THE TARGET.

EACH OUTPUT CORRESPONDS TO TRANSMITTED SIGNAL ATTENUATION OF 20 DB OVER THE NEXT LARGEST OUTPUT.

INPUT SIGNAL TO NOISE RATIO IS APPROXIMATELY UNITY FOR LARGEST OUTPUT.

CONCLUSION

The results of this research have shown that a simple correlation type ultrasound receiver can detect echoes which have at least 8000 times less power than the thermal receiver noise without any noticeable problems due to mechanical vibration or electronic instabilities. Several further orders of magnitude improvement in sensitivity may be possible by simply lengthening the system integration time above the 0.1 sec used in this work and using a larger mark-space ratio for the transmitted signal.

Following the work originally done for radar, it has been established that when using noise as the transmitted signal, no range ambiguities exist, so that a signal can be transmitted almost continuously. This lessens the peak to average transmitted power to near unity, thus lessening the risk of transducer electrical breakdown. It has also been shown that piezoelectric transducers transmitting noise can produce the same range resolution as when transmitting periodic bursts of r.f. having the same spectral density. Furthermore a clutter avoidance technique which has not been used in radar has been described which should make it possible to transmit noise almost continuously without deterioration of the system response due to clutter type echoes from flaws situated outside the system range cell. It has also been established that the system can easily detect the presence of 25 micron wire flaws which are far smaller than its present lower resolution limit of 250 microns.

When operating at high resolution, the system described can trade speed for sensitivity by varying the integration time of the correlator output. When examining objects which are expected to contain a very small number of possible flaws, increased speed can be obtained without sacrificing sensitivity, by narrowing the transmitted spectrum, thus enlarging the range cell.

The fact that the system has much greater sensitivity and uses much lower peak to average transmitted power than conventional systems should enable it to greatly extend the size of strongly absorbing objects that can be examined by ultrasound, or to use higher frequencies which are too strongly absorbed to be practical at present, and thus obtain greatly improved resolution. The ability of a random signal correlation system to provide high sensitivity for a given transmitted power also makes it possible to reduce the peak and average power required for a given sensitivity. This feature and the absence of range ambiguity may make such systems of interest for organ scanning, particularly in the case of the brain, where the skull produces undesirably large absorption and reverberation. Other advantageous applications of random signal correlation systems to medicine may exist in the case of blood flow measurement.

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APPENDIX

The signal noise ratio enhancement of the clipped random signal correlation receiver used in this work may be calculated as follows. Referring to Fig. 1, we may assume that the transmitted signal, $x(t)$, is simply a sample function from a stationary, zero mean random process generated by a noise source. For purposes of the present discussion, this source will be assumed to be Gaussian although this is primarily an analytical convenience rather than a practical necessity. The system would work equally well, or better, with almost any other probability density function. A portion of the transmitted signal is delayed to form the reference signal, $r(t)$, and after clipping it provides one input to the correlator which is of the polarity coincidence type.

The signal produced by the receiving transducer, which may be the same one as that used for transmitting, is amplified and becomes $y(t)$, which after clipping, becomes the other input to the correlator. This signal consists of the portion of $x(t)$ that is reflected from any target plus system noise. The output of the correlator, $z(t)$, contains the cross-correlation function of the clipped forms of $y(t)$ and $r(t)$. The signal $y(t)$ includes a noise portion $n(t)$, which comes both from the echo amplifier thermal noise, and from clutter echoes.

The ultrasound target may be represented quite generally as a multitude of discrete reflecting points located at different ranges. The return from any particular point, say the kth one, may be represented as $a_k x[t - \tau_k(t)]$ where a_k depends upon the magnitude of the reflection and

$\tau_k(t)$ is the round trip delay encountered by this particular return. If there are N such reflecting points, the total echo signal becomes

$$y(t) = \sum_{k=1}^{N} a_k \, x\left[t - \tau_k\right] + n(t) \qquad 1\text{-}1$$

where n(t) is the system noise, which is assumed to have variance and power σ_n^2.

The reference signal, r(t), is a delayed version of the transmitted signal. Thus it may be represented as

$$r(t) = x\left[t - \tau_r\right]$$

In the basic random signal system an analog correlator would perform the multiplication of the received signal y(t) and the reference signal r(t), giving an output

$$z_a(t) = y(t)\, r(t) = \sum_{k=1}^{N} a_k \, x\left[t - \tau_k\right] x\left[t - \tau_r\right] + n(t)\, x\left[t - \tau_r\right] \qquad 1\text{-}2$$

Since x(t) and n(t) are statistically independent, zero-mean random variables, the expected value of their product will be zero. Therefore the expected value of the output of an analog correlator system would be

$$E\left\{z_a(t)\right\} = R_{ry}(t) = \sum_{k=1}^{N} a_k \, R_x\left[(\tau_r - \tau_k)\right] \qquad 1\text{-}3$$

where R_{ry} ( ) is the cross correlation of y(t) and r(t), and R_x( ) is the autocorrelation function of x(t).

In considering the signal to noise ratio associated with the response to one target only, it is valid to assume that the returns from all other targets outside the range cell, are just part of the added noise n(t).

This is analogous to letting N = 1 in Eq. 1-2 in which case this becomes

$$z_a(t) = a_1 x[t - \tau_1]\, x[t - \tau_r] + n(t)\, x[t - \tau_r] \qquad 1\text{-}4$$

and the expected value of this is

$$E\{z_a(t)\} = a_1 R_x[(\tau_r - \tau_1)]$$

If the reference delay of the system is adjusted to equal τ_1, the output of an analog correlator fed with unclipped signals would have a peak value given by

$$E\{z_p\} = a_1 R_x(0) = a_1 \sigma_x^2 \qquad 1\text{-}5$$

where σ_x^2 is the variance and power of the transmitted signal.

In the experimental system the analog signals r(t) and y(t) are first clipped and then passed through a polarity coincidence correlator whose output corresponds to the product of the clipped inputs. According to a well known result[19] the expectation value of this product can be written as

$$E\{z(t)\} = \frac{2}{\pi} \sin^{-1} \frac{R_{ry}(t)}{\sigma_x \sigma_y} \qquad 1\text{-}6$$

where σ_y^2 is the variance of the echo amplifier output and is given by

$$\sigma_y^2 = a_1^2 \sigma_x^2 + \sigma_n^2 \qquad 1\text{-}7$$

From 1-3, 1-5 and 1-6 the peak output of the polarity coincidence correlator which occurs when τ_r is adjusted to equal τ_1 is a d.c. signal given by

$$E_p\left\{z_p\right\} = \frac{2}{\pi}\sin^{-1}\frac{a_1\sigma_x}{\sigma_y}$$

$$\sim \frac{2}{\pi}\,\frac{a_1\sigma_x}{\sigma_y} \qquad 1\text{-}8$$

for the practical case where the echo amplifier output signal to noise ratio is much smaller than unity.

Having derived the peak signal output of the polarity coincidence correlator it remains to calculate its noise output. Under conditions of small input signal to noise ratio, one of the correlator inputs consists mostly of clipped noise. This will be assumed to have the same bandwidth B as the transmitted signal. The random portion of the correlator output will thus be in the form of a binary signal which changes from +1 to -1 at random intervals. The spectral density of such a waveform is well known to be

$$S(f) = \frac{B/\pi}{B^2 + f^2}$$

Since the correlator is followed in our system by a low pass filter whose bandwidth may be taken as W, the system output noise power will be

$$\sigma_o^2 = 2W\,S(0) = \frac{2W}{\pi B}$$

The signal to noise power ratio referred to the system input is the same as that at the output of the echo amplifier and is given by

$$(SNR)_i = \frac{a_1^2\,\sigma_x^2}{\sigma_n^2}$$

The system output signal to noise ratio is seen from eqn. 1-8 to be

$$(SNR)_o = \frac{\left(\frac{2}{\pi} \frac{a_1 \sigma_x}{\sigma_y}\right)^2}{\sigma_o^2}$$

$$= \frac{2}{\pi} \frac{B}{W} \frac{1}{1 + (SNR)_i^{-1}}$$

$$\sim \frac{2}{\pi} \frac{B}{W} (SNR)_i$$

since $(SNR)_i$ has been assumed to be much less than unity.

If the transmitted signal instead of being continuous has a mark-space ratio α and if the integration time of the filter is

$$T = 1/W$$

we finally obtain the correlation gain of the clipped random signal flaw detection system as

$$\frac{(SNR)_o}{(SNR)_i} = \frac{2\alpha}{\pi} BT$$

This correlation gain is seen to be a factor of $2/\pi$ smaller than the value of αBT which is known to hold for both deterministic and random signal analog correlation receiver producing a d.c. signal.

FOOTNOTES

[A] The term 'clipping' is used here and subsequently to refer to the process in which a zero mean analog signal is transformed into a binary signal having the same zero crossings.

[B] The range cell is that region of space from which the scattered signal will correlate with the delayed version of the transmitted signal.

[C] For a clutter avoidance system in which the transducer beam patterns overlap at a small region only, they will have to be moved physically, at the same time as the delay line length is varied. Electronic techniques for moving the beam pattern intersection point might also be possible.